

Climate Affection on Bird Population
(Using differential equations)

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Acknowledgment

First and foremost, praises and thanks to God, the Almighty, for His showers of blessings throughout our research work to complete the research successfully. We would like to express our deep and sincere gratitude to our research supervisor, DR. Ethar, for allowing us to do research and providing invaluable guidance throughout this research.

He has taught us the methodology to carry out the research and to present the research work as clearly as possible. She was the one who encouraged us to work on this project, and without her, this wouldn't have been possible. We're also grateful to our TA: Amr Elazzazy and JTA: Hassoon who has helped us with the prototyping phase and given us practical insights into how to work in the lab, taking the precaution of all safety measures as safety is always the priority. Finally, we would like to thank our parents for their generous support throughout the journey of this research. This project would not have come so far within the prescribed time without support from all the people; we are indebted to you all. We hope this small project will make a significant impact by inspiring someone else to build upon our research

With sincere thanks

Abstract

When a population is far from its limits of growth it can grow exponentially. However, when nearing its limits the population size can fluctuate, even chaotically. Migratory birds are a perfect example of this situation. Many migratory birds perished in the summer of 2020 because of expanding wildlands and unexpected cold weather. Migratory birds struggle with heat stress in August 2020 because of the hot conditions brought on by uncontrolled radiation and marine evaporation. Before they were physically prepared for their long-distance migration, the heat and smoke of the wildlands caused the migrating birds to go to feeding sites in favor of land regions, where water and food are not available.

Introduction

One of the most fundamental factors at work in ecology is seasonal variation. Temperature cycles that occur repeatedly produce brief windows of opportunity during which vital processes like breeding and blooming can take place. The ability of many animals to breed successfully depends on the ability of their offspring's nutritional needs to coincide with a time when food is abundant [1]. By utilizing geographically unique places at various times of the year, migratory populations can successfully define an annual existence infrastructure that would otherwise be unusable, reducing the negative effects of seasonal fluctuation. However, this strength might turn into a weakness in the event of severe climate change. Typically, migrants use their own internal cues and/or external clues to determine when it is time to leave a certain area [2]. If these cues are no longer reliable indications of the conditions at their destination, this dependency might become maladaptive [3]. In this research, we will explain the relationship between bird migration and climate in response to changes in habitat, food availability, climate, and other factors.

The earliest feasible breeding date for migratory species is determined by the time at which they arrive

at the breeding grounds. The capacity to change the schedule of one's arrival is typically less flexible for long-distance migrants than it is for short-distance migrants [7]. The fact that the signal for leaving the wintering area is temperature independent is one explanation for this; hence, their arrival time does not advance to allow for the earlier ideal breeding time [8]. Long-distance migrants have been shown to modify their migratory cues to restriction, yet there is still some evidence to support this. It seems like the exception rather than the rule is this. Many long-distance migrants are unable to reach their mating grounds at the ideal time due to the decoupling of phenological signals caused by climate change [9], which causes sharp population decreases [10]. The ability of short-distance migrants to change the timing of important events appears to be less constrained [11]. The ability of these species to enter the breeding areas early allows them to use temperature as a prediction of the ideal breeding period. The effects of climate change, however, could not be uniform throughout various seasons. In this situation, the time of the food season may no longer be accurately predicted by the temperature at the start of the season, leading to a mismatch [12]. For example, such temporal irregularities have been connected to reproductive failure in a population of great Mammals [13].

The current study aims to pinpoint the key variables and investigate how shifting environmental conditions

affect the effectiveness of migration tactics. We employ a model that was previously created for bird migration [23] and includes variables that are pertinent to the environmental circumstances at the locations of the stopovers. We assess the sensitivity of the model regarding the parameters characterizing migratory patterns and environmental factors. As a result, we investigate, using

simulations and sensitivity analysis, how environmental changes affect bird migration and how shifting migratory tactics affect reproductive success.

Literature Review

The differential equations for biomass and population densities of groups of migrating birds—if storks fly in groups for at least some of the migratory route for safety and energy reasons—are the main equations used to describe the behavior of bird populations. Population density is defined as biomass divided by the average mass of a bird. This density represents the amount of fat and energy that the birds have stored. The relationship between biomass and population density, which sets our model apart from more traditional logistic growth models, derives from the mass dependence on reproduction and mortality rates. The male, female, and nestling populations are handled differently in our model.

Population Dynamics and Biomass:

We describe changes in **Equation (1)** population density considering the following processes:

Birth - death + immigration (due to migration) – emigration (due to migration)

This balance can be formulated as a differential equation:

$$\frac{dx_{i,j}}{dt} = x_{i,j}\beta_{i,j}(t, m_i)(1 - s_j) - \delta_i(m_i)x_{i,j} - \mu(t)x_{i,j} + x_{i,j}(t)$$

Equation (2) is a logistic equation in which we keep birth and death rates separate, since reproduction happens during the breeding season only, whereas death processes occur variably throughout the year.

In order to describe the change in biomass of the adult population, we consider the following processes:

Feeding- metabolism- laying eggs (for females only) – deaths + juveniles reaching adulthood – emigration (due to migration) + immigration (due to migration)

Juveniles are considered part of the adult population when they start feeding independently. As previously mentioned, we modeled the growth of nestlings separately.

Considering the processes in the preceding list, the change in biomass appears as follows:

$$\frac{d}{dt}b_{i,j} = x_{i,j}(-\beta_{i,j}(t, m_i)(1 - s_j) * m_{egg} + \phi_{-y}) - v - \delta_i(m_i)b_{i,j} + x_{i,j,juv}(t)m_{juv} - \mu(t)b_{i,j} + b_{i,a}(t)$$

Finally, the adult birds' average body mass m is

$$m = \frac{\beta_{i,j}(t)}{x_{i,j}(t)}$$

Latitude and temperature turned out to be the two strongest individual factors along which bird numbers fluctuated, however latitude and longitude were generally inversely linked with both

resident bird densities and factors affecting temperature and precipitation. The concentrations of many resident birds decreased with increasing latitude or decreasing temperatures. Latitude appeared to be the more important of the two parameters, according to partial correlation analysis. Both the resident and migrant bird populations declined as one moved further north, but the resident population fell more precipitously. In the north, resident bird populations made up only a small portion of breeding bird populations, whereas in the south they frequently make up half of breeding bird populations. The key conclusion Latitude was the most effective factor of resident densities.

For this reason, it turned tough to split the relative impact of every person's component, due to the fact that range in part describes all the unique variables (temperature and precipitation). The outcomes recommended that precipitation turned into much less significance and that the interaction between range and ambient temperatures turned into now no longer the only component at the back of the robust impact of range. We advise that the coupled impact of harshening weather and lowering quantity of to-be-had strength with growing range is restricting the populace sizes of resident birds. We additionally advocate that the impact of these elements is maximum obvious in northern Fennoscandia, in which resident densities are recommended to be decreased than might be predicted on the idea of summer season wearing capacity.

If $k < 0$ (that is, if x decays), then e^{kt} approaches 0 as t becomes very large, so

$$\lim_{t \rightarrow \infty} x = \lim_{n \rightarrow \infty} (C e^{kt} - m) = -m.$$

Thus, x approaches $-\frac{m}{k}$, which is called the equilibrium value. On the other hand, if $k > 0$ (that is, if x grows), then x approaches the equilibrium value $-\frac{m}{k}$ as $t \rightarrow -\infty$

Flow model:

The continuity equation (equation (2.1)) defines the transit of a conserved quantity (such as bird density) based on the principle of mass conservation: the rate of change of this quantity is equal to its flow into and out of a given volume (e.g., sky). A source/sink term, which considers the quantity's presence (and disappearance), may also be included in the equation (e.g., take-off and landing). The continuity equation for the number of birds per square kilometer has a differential form, which is

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{v}) + W, \quad 2.1$$

Where W is the source/sink term [birds h⁻¹ km²] and $\mathbf{v} = [v_{lon}, v_{lat}]$ is the bird velocity field [km h⁻¹] along latitude and longitude and represents the vector differential operator. The forward time-centered space (FTCS) technique is used to discretize the continuity equation [33]. For each cell i, j , and t , the source/sink term can be calculated with

$$W_{t,i \rightarrow j, t+1} = \rho_{i,j,t} \left(\frac{\Delta t}{\Delta x} (v_{lon}|i,j,t+1/2| - v_{lon}|i,j,t-1/2|) + \frac{\Delta t}{\Delta y} (v_{lat}|i,j,t+1/2| - v_{lat}|i,j,t-1/2|) \right) + 2 \frac{\Delta t}{\Delta x \Delta y} (\phi_{lat}|i,j,t+1/2| - \phi_{lat}|i,j,t-1/2|) + 2 \frac{\Delta t}{\Delta x \Delta y} (\phi_{lon}|i,j,t+1/2| - \phi_{lon}|i,j,t-1/2|), \quad 2.2$$

where the flow term, denoted by the indexes I, j , and t , is discretized into longitude, latitude, and time and expressed as $[\text{birds km}^{-1} \text{h}^{-1}]$. The grid resolution is expressed in terms of longitude, latitude, and time, respectively.

Using Spatio-temporal maps of bird density (ρ) and flight speed vector (\mathbf{v}) produced by geostatistical simulations (2.2), we used this model for the migration of birds. The density was multiplied by the flight vector to calculate the local fluxes for each grid cell, and the latitudinal and longitudinal components were then linearly interpolated to the grid cell boundaries. We consider the variable resolution of Lon in km along the latitude axis in the discretization because the grid was designed with equal latitude and longitude intervals. The source/sink term was then calculated for each grid cell at each time step using equation (2.2) as the change in bird density with time minus the spatial difference of fluxes. Birds taking off and landing (within the study area) were the source/sink term W , and they can be distinguished based on the sign of W . In fact, because the sky served as the mass balance's reference point, positive values of W are consistent with birds taking off, whereas negative

values are consistent with birds landing. In addition, we extracted the values of the rivers bordering the study area as the number of birds entering and leaving the study area (positive) and exiting (negative). Using 500 simulations, Spatial-temporal maps of [1] takeoff and landing [birds km⁻²] and [2] latitude and longitude fluxes [birds h⁻¹ km⁻¹] were created in the study boundary area. did.

Arctic Terns are breeds in Alaska and the Northern parts of Canada. However, they don't stay very long as these birds move around a lot. They are also not seen anywhere south of their breeding grounds. These birds can be found anywhere near the ocean, rocky coasts, small islands, and anywhere else with very few trees. They find food in the water, hovering around 30-40 feet above the sea, before diving in to catch small fish to eat. Their movement starts in summer from their coastal breeding grounds going west to the southernmost point of South America. The birds then migrate across the North Atlantic Ocean, going to Europe and northern Africa. The birds will then head farther down south, going to the southern part of Australia, New Zealand, and Antarctica.

Crossing the Pacific, they reach back to their breeding grounds in the Arctic Circle and northern parts of America. If you look at the Arctic Tern's migration pattern, it's truly a long journey for these little birds. So, why do they go through all this trouble going circle around the world? It turns out that the Arctic Terns migrate by following the summer sun. This way, they don't experience any winter or significant temperature changes. It wouldn't also be harder for them to find food in summer, compared to when they must experience winter while in the Arctic. It's a survival tactic for these birds. But the fact that they are lightweight and mostly glide in the air makes long-distance travel easier than other birds. They don't use a lot of energy compared to birds who need to flap their wings continuously. It's also found that Arctic Terns can fly 1,000 miles without stopping.

Methodology

Migratory bird population $P(t)$ = birth – death – emigration of migratory birds

$$\frac{dP(t)}{dt} = k_1 * P(t) - k_2 * P(t) - E(t) * P(t) \quad (1)$$

K_1 : constant of birth rate K_2 : constant of death rate $E(t)$: variable of emigration rate t : time We

found that the migration rate is directly proportional to the temperature of the season:

$$E(t) \propto T(t) \quad E(t) = k_3 T(t) \quad (2) \quad K_3: \text{constant of temperature variable}$$

We can make a basic model of the temperature of the Earth by assuming that it receives incoming insolation (solar energy) but radiates some of it back into space. The global mean temperature T can be modeled by the energy balance equation (EBM).

$$R \frac{dT}{dt} = Q(1 - \alpha) - \epsilon T^4$$

- T (K, kelvins) is the average temperature in the Earth's photosphere (upper atmosphere, where the energy balance occurs in this model) (1 kelvin = 1
- t (years) is time.
- R (W-yr./m²K) is the averaged heat capacity of the Earth/atmosphere system (heat capacity is the amount of heat required to raise the temperature of an object or substance 1 kelvin (= 1
- Q (W/m²) is the annual global mean incoming solar radiation (or insolation) per square meter of the Earth's surface.

- α (dimensionless) is planetary albedo (reflectivity),
- σ (W/m²K⁴) is a constant of proportionality, the Stefan-Boltzmann constant.

The first term on the right is incoming heat absorbed by the Earth and its atmosphere system. The second term is heat radiating out as if the Earth were a blackbody with all the outgoing longwave radiation (OLR) escaping to space.

By substituting (2) in (1)

$$\frac{dP(t)}{dt} = k_1 * P(t) - k_2 * P(t) - k_3 * T(t) * P(t)$$

Results

We solved the equation analytically as following:

First, We calculated the equation (3) by substituting

$$R = 2.912 \quad [26]$$

$$Q = 342 \quad [25]$$

$$\alpha = 0.3 \quad [25]$$

$$\sigma = 5.67 \times 10^{-8} \quad [27]$$

We found that we can solve T(t) analytically as following:

$$2.914 \frac{dT}{dt} = 342 * (1 - 0.3) - 5.6 * 10^{-8} * T^{-4}$$

$$2.914 * \frac{dT}{dt} = 239.4 - 5.6 * 10^{-8} * T^{-4}$$

$$\frac{dT}{dt} = 81.9863 - 1.91780 * 10^{-8} T^{-4}$$

$$\frac{dt}{dT} = \frac{1}{81.9863 - 1.91780 * 10^{-8} T^{-4}}$$

$$\int dt = \int \frac{dT}{81.9863 - 1.91780 * 10^{-8} T^{-4}}$$

$$t + c1 = \frac{243}{100000} * T^5$$

$$T(t) = \frac{10}{3} \sqrt[5]{t + c1} \quad (5) \quad , c1 \rightarrow \text{constant}$$

Second: After Substituting equation (5) in (4)

$$\frac{dP}{dt} = k_1 * P(t) - k_2 * P(t) - k_3 * \frac{10}{3} \sqrt[5]{t + c_1} * P(t)$$

$$\frac{dP(t)}{dt} = \left(k_1 - k_2 - \frac{10}{3} k_3 * \sqrt[5]{t + c_1} \right) P(t)$$

$$\frac{dP}{P} = \left(k_1 - k_2 - \frac{10}{3} k_3 * \sqrt[5]{t + c_1} \right) dt$$

$$\ln(p) = k_1 * t - k_2 * t - \frac{10}{3} * k_3 \frac{(t + c_1)^{1.2}}{1.2} + c_2$$

$$P(t) = e^{k_1 * t - k_2 * t - \frac{10}{3} * k_3 \frac{(t + c_1)^{1.2}}{1.2} + c_2} \quad (6)$$

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